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[54] COMPUTER DRIVEN OPTICAL KERATOMETER AND METHOD OF EVALUATING THE SHAPE OF THE CORNEA

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[73] Assignee: **California Institute of Technology**, Pasadena, Calif.

[21] Appl. No.: **170,215**

[22] Filed: **Mar. 17, 1988**

[51] **Int. Cl.**[5] **A61B 3/10**

[52] **U.S. Cl.** **351/212**; 351/221

[58] **Field of Search** 351/212, 221, 246

[56] **References Cited**

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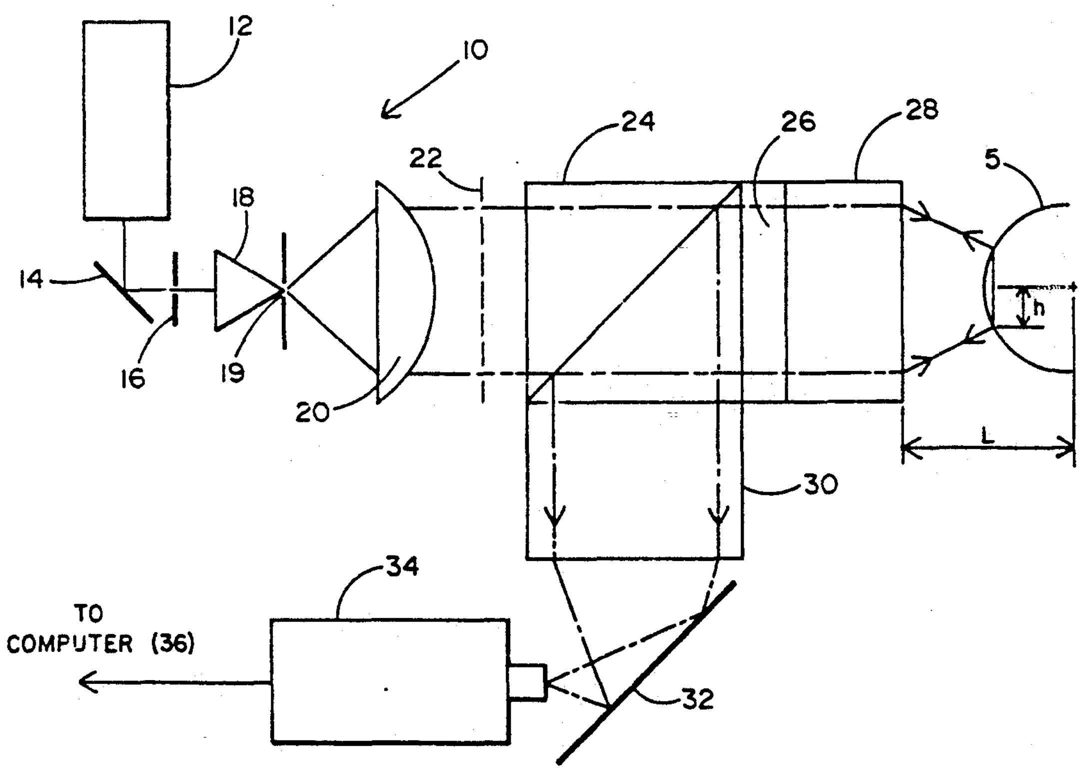
Attorney, Agent, or Firm—Leonard Tachner

[57] **ABSTRACT**

An apparatus and method for measuring the shape of the cornea utilize only one reticle to generate a pattern of rings projected onto the surface of a subject's eye. The reflected pattern is focused onto an imaging device such as a video camera and a computer compares the reflected pattern with a reference pattern stored in the computer's memory. The differences between the reflected and stored patterns are used to calculate the deformation of the cornea which may be useful for pre-and post-operative evaluation of the eye by surgeons.

16 Claims, 5 Drawing Sheets



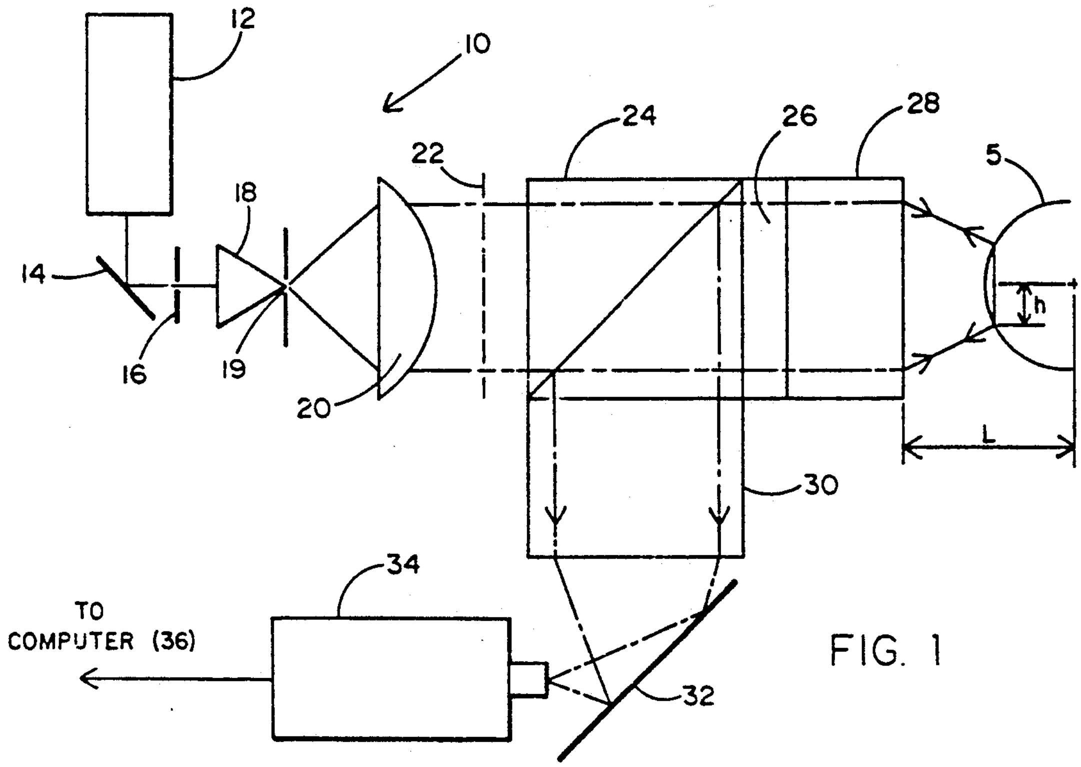


FIG. 1

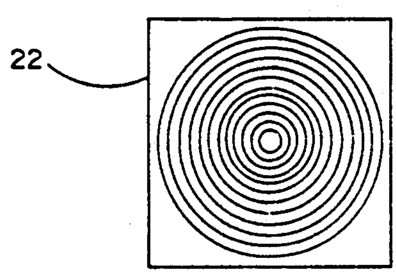


FIG. 1a

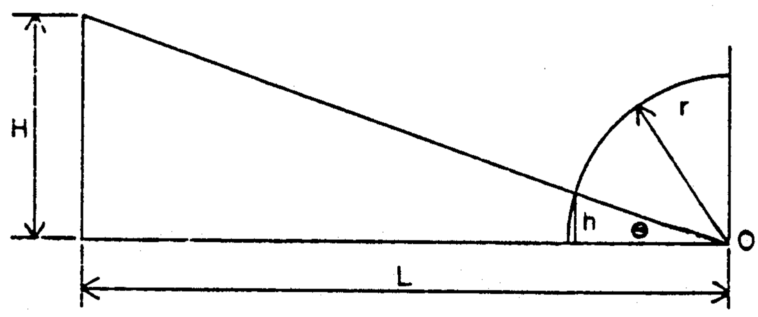


FIG. 2

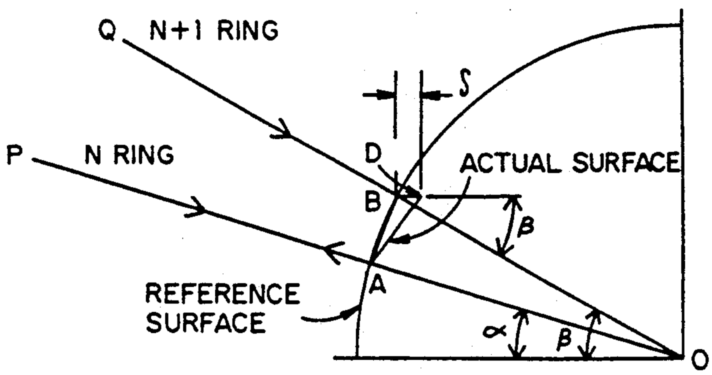


FIG. 4

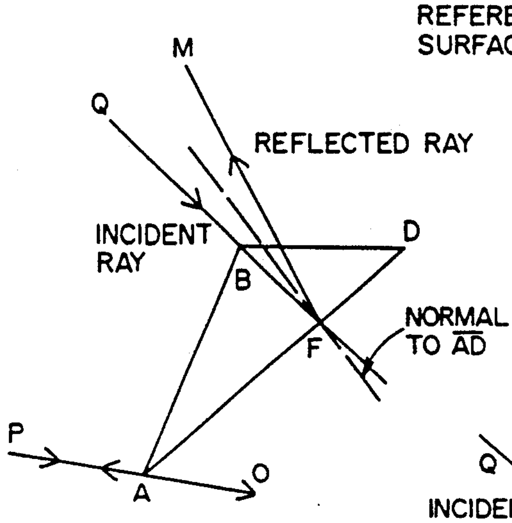


FIG. 4a

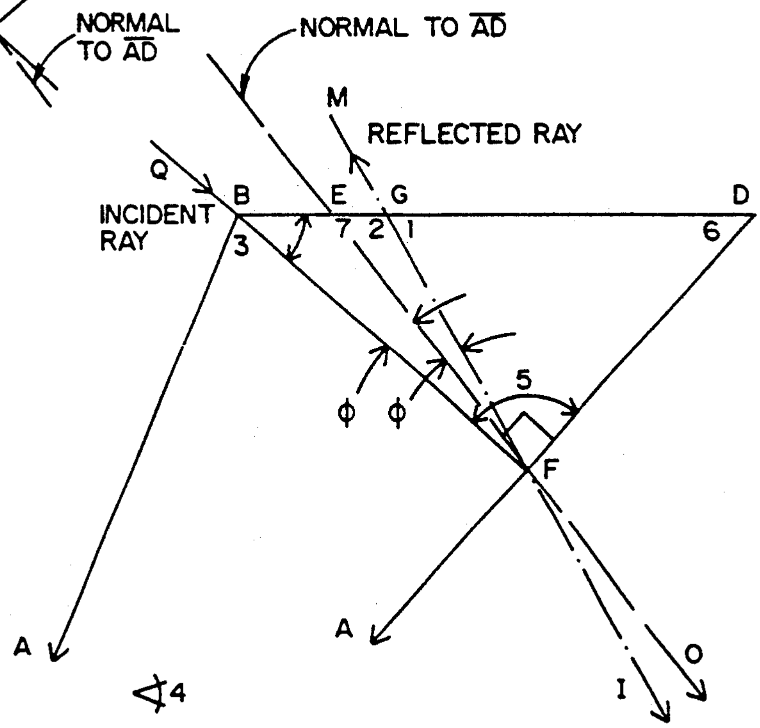


FIG. 4b

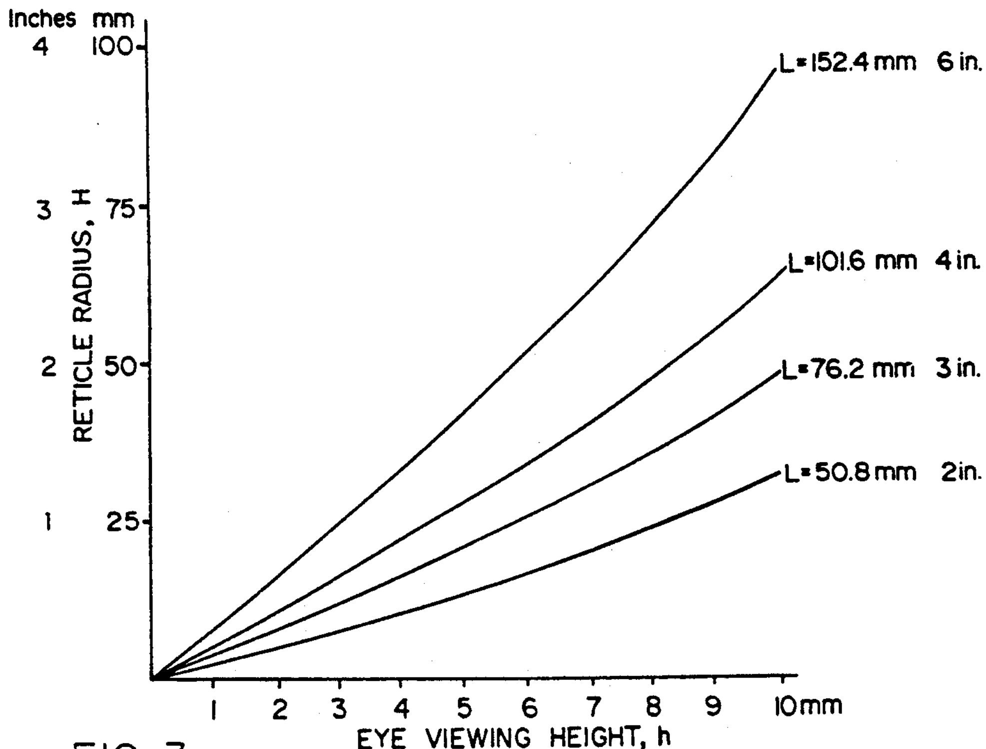

Inches mm
4 100
3 75
2 50
1 25
RETICLE RADIUS, H
L=152.4 mm 6 in.
L=101.6 mm 4 in.
L=76.2 mm 3 in.
L=50.8 mm 2 in.
1 2 3 4 5 6 7 8 9 10mm
EYE VIEWING HEIGHT, h

FIG. 3

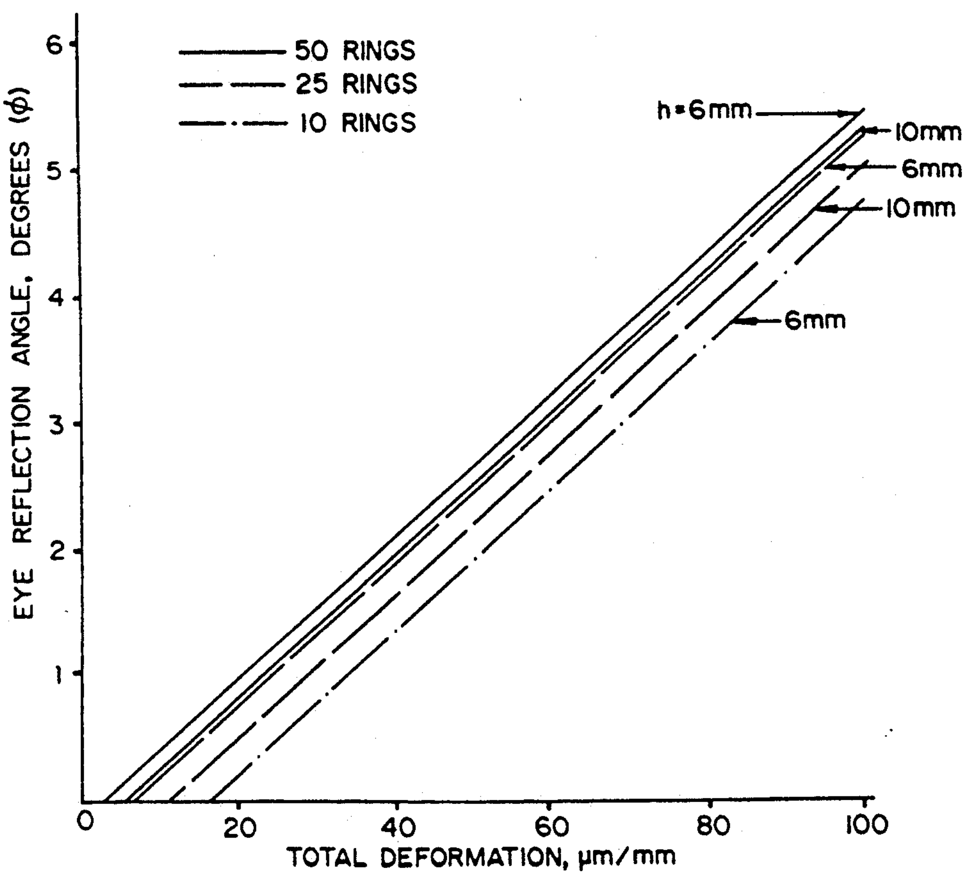

50 RINGS
25 RINGS
10 RINGS
h=6mm
10mm
6mm
10mm
6mm
6 5 4 3 2 1
EYE REFLECTION ANGLE, DEGREES (φ)
0 20 40 60 80 100
TOTAL DEFORMATION, μm/mm

FIG. 5

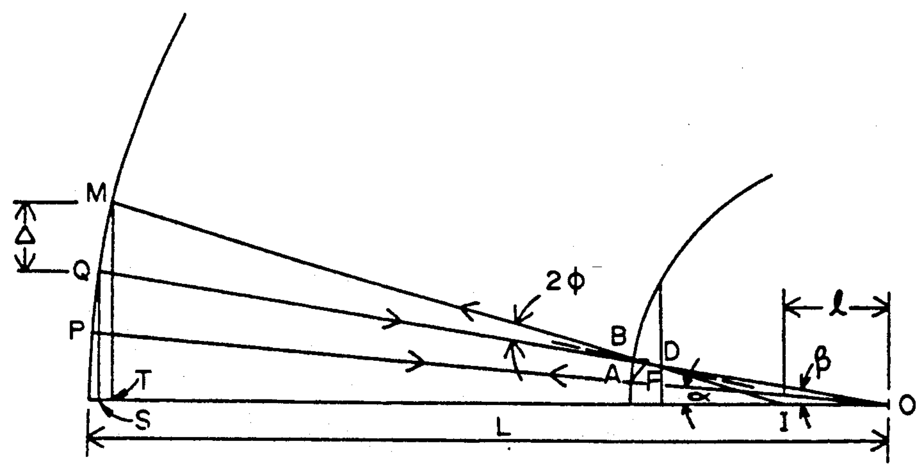

M
Δ
Q
P
T
S
2φ
B
D
A
F
α
β
ℓ
I
O
L

FIG. 6

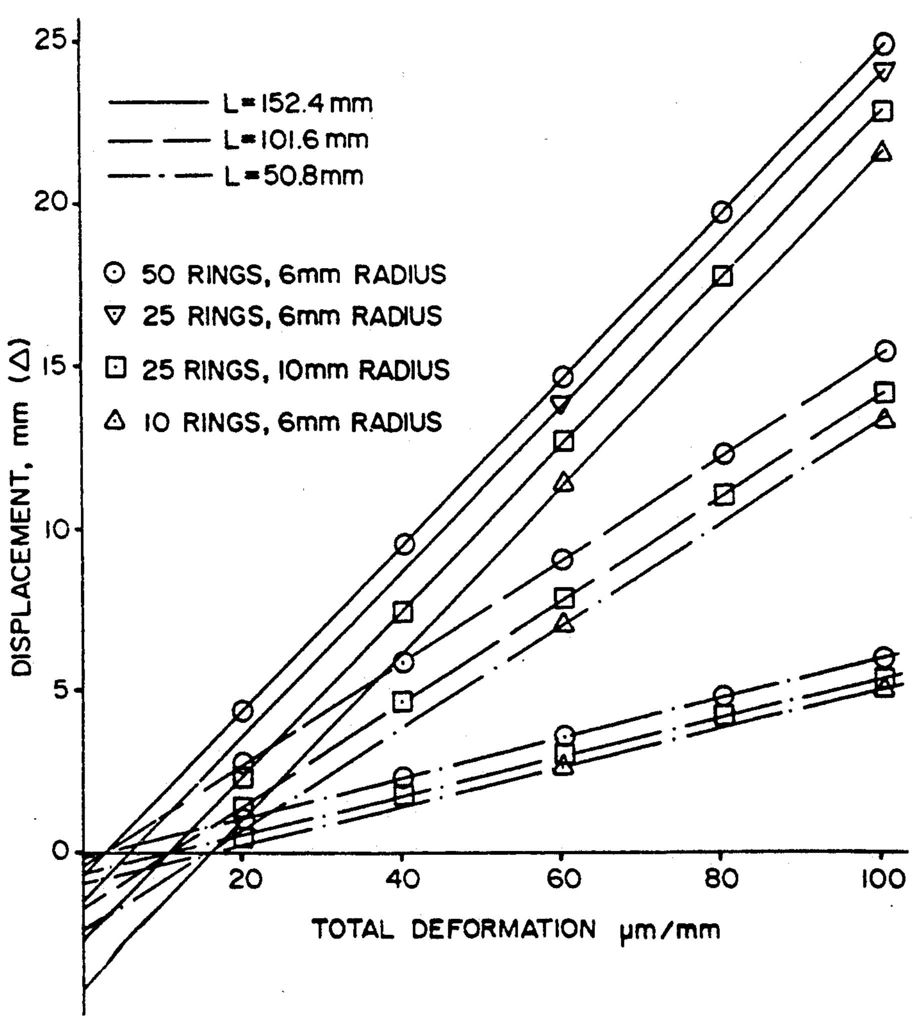

L=152.4 mm
L=101.6 mm
L=50.8mm
50 RINGS, 6mm RADIUS
25 RINGS, 6mm RADIUS
25 RINGS, 10mm RADIUS
10 RINGS, 6mm RADIUS
DISPLACEMENT, mm (Δ)
TOTAL DEFORMATION μm/mm
0
5
10
15
20
25
20
40
60
80
100

FIG. 7

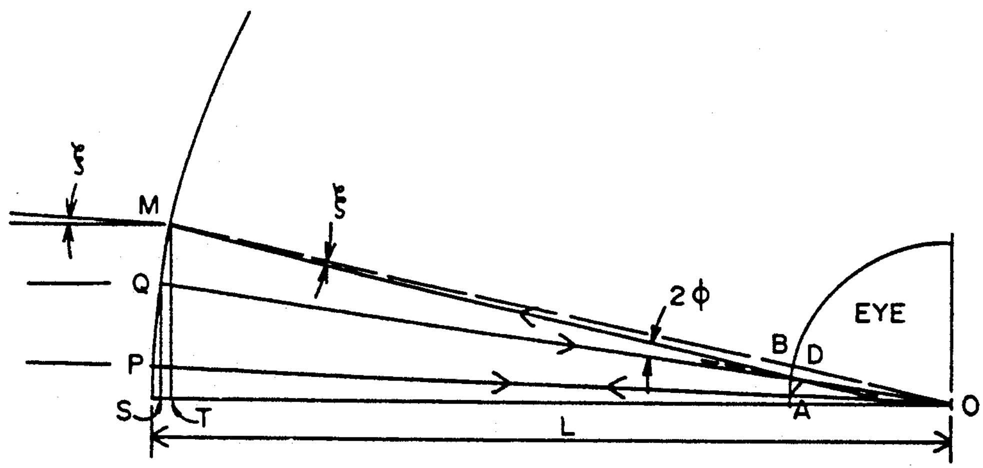

ξ
M
ξ
Q
2φ
EYE
P
B
D
S
T
A
O
L

FIG. 8

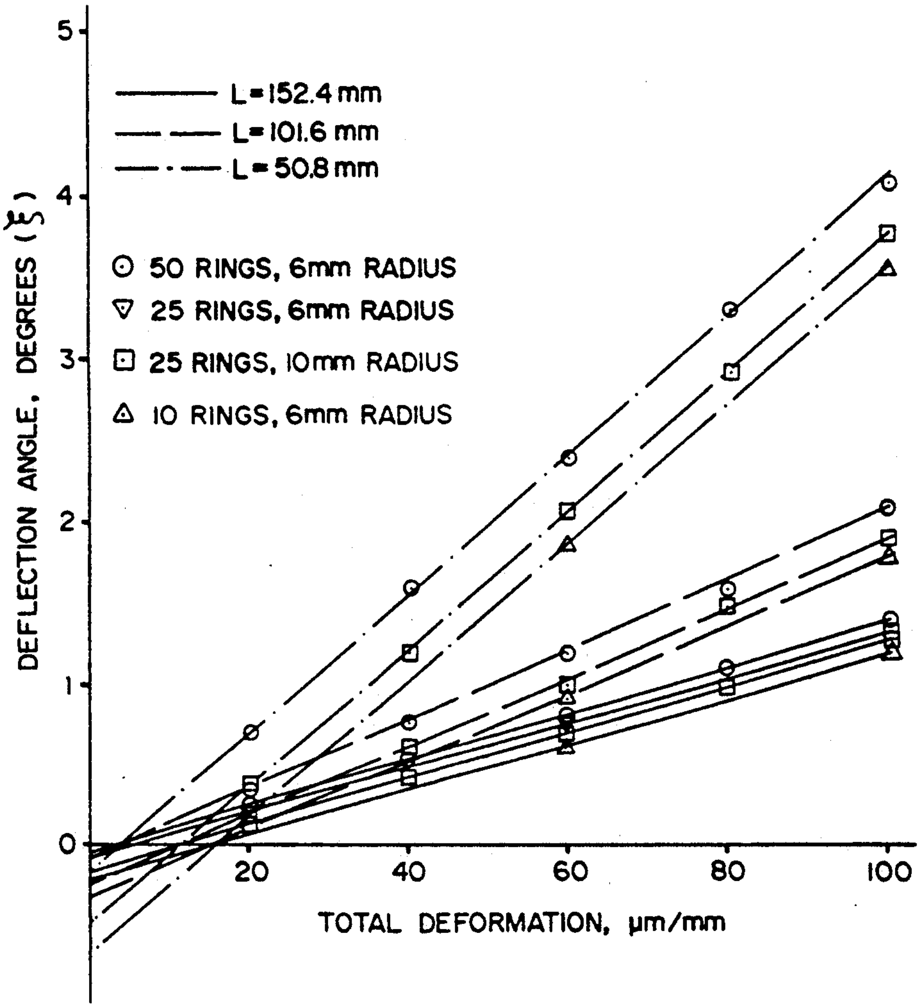

L=152.4 mm
L=101.6 mm
L=50.8 mm
50 RINGS, 6mm RADIUS
25 RINGS, 6mm RADIUS
25 RINGS, 10mm RADIUS
10 RINGS, 6mm RADIUS
DEFLECTION ANGLE, DEGREES (ξ)
TOTAL DEFORMATION, μm/mm
0
1
2
3
4
5
20
40
60
80
100

FIG. 9

COMPUTER DRIVEN OPTICAL KERATOMETER AND METHOD OF EVALUATING THE SHAPE OF THE CORNEA

ORIGIN OF INVENTION

The invention described herein was made in the performance of work under a NASA contract, and is subject to the provisions of Public Law 96-517 (35 USC 202) in which the Contractor has elected to retain title.

TECHNICAL FIELD

The present invention relates generally to keratometry, that is, measurement of the cornea of the human eye and more specifically, to a laser keratometer having an optical subsystem designed to impose a reticle-generated series of rings on the eye and capture a series of reflected rings from the eye. A computer-stored reference image is effectively superimposed on the image reflected from the subject's eye so that computer processing provides means for generating either real time or near real time information on the eye shape.

BACKGROUND ART

Corneal surgery is currently undergoing rapid evolution with improvements designed to minimize or eliminate astigmatism following penetrating keraplasty (corneal transplants), as well as to correct refractive error. Because the cornea is the most powerful refracting surface of the eye, numerous procedures have been devised to incise, lathe, freeze, burn and reset the cornea to alter its shape. Currently practiced keratorefractive surgical techniques include: cryorefractive techniques (keratomileusis, keratophakia, ipikeratophakia), radialkeratotomy, thermal keratoplasty, corneal relaxing incisions and wedge resections.

When preparing the patient for any of these surgical techniques, it is essential to accurately measure the corneal curvature. Existing methods to measure corneal curvature include central keratometry and photokeratoscopy with central keratometry. However, with these methods only the central three millimeters of the cornea is measured. Recently, photokeratoscopy has been adapted to provide a topographic map of the cornea. However, this technique in its present form provides only a qualitative assessment of the cornea. This is because while photographs can be analysed by computer techniques or manual tracing, the time delay and effort in producing such data reduces the utility of the method for measuring corneal curvature preoperatively and for evaluating the effect of surgical techniques post-operatively. Thus, there is an ongoing need for a real time keratometer system for medical diagnosis and for preparation of the corneal contour for eye surgery as well as for post-operative analysis of completed eye surgery. One example of a computerized laser keratometer of the prior art utilizes a computer to analyse the moire patterns generated by laser excitation of the corneal surface and the resulting projecting and reflected beams. Unfortunately, such prior art devices have alignment problems as well as problems due to fringes that result from misalignment.

SUMMARY OF INVENTION

The system of the present invention provides a configuration that is somewhat similar to that of a classic keratometer, but with a novel optical system that illuminates through a shuttered light source and a focusing assembly and a sensor in the form of a solid state imager arranged to accept the image created by reflections from several zones of the cornea. A reference image is stored in a computer memory. The numerical superposition of the stored image on the reflected image from the subject's eye is displayed in real time or processed by the computer to yield numerical information regarding deformation of the eye. The novel approach of the present keratometer requires only one optical reticle which results in a substantial simplification in the optical system. Only the reflected ring pattern is required to be processed by the optical system. Since a reference reticle is generated and stored in the computer, the computer determines the center of the reflected ring pattern and overlays it precisely on the center of the reference ring pattern. Fringes due to misalignment are thus obviated in the present invention and only fringes due to deformation appear.

The present optical system imposes a series of rings generated by the reticle on the eye and captures a series of reflected rings. If no cornea deformation exists there is no displacement of the rings reflected from the eye from the reference set of rings stored in the computer. Any deformation causes some or all of the rings to be displaced slightly from the reference set and the computer determines the amount of deformation. In one particular embodiment disclosed herein, the apparatus comprises a helium-neon laser, a shutter, a reticle, a beam splitter, a quarter-wave plate and focusing assemblies. The reticle comprises a chrome deposited array of circular rings. Furthermore, in the particular embodiment disclosed herein the optical sensor or imager comprises a CCD video camera the output of which is eventually applied to a computer which is programmed to carry out the software routine disclosed herein for numerically analyzing the deformation of the observed cornea surface based upon displacement between the reflected image and the stored reference image.

OBJECTS OF THE INVENTION

It is therefore a principal object of the present invention to provide a computer driven optical keratometer as an evaluation tool for assessing the shape of the cornea primarily for pre-and post-operative evaluation in conjunction with corneal eye surgery.

It is an additional object of the present invention to provide a computer driven optical keratometer in which a reticle-induced series of rings is reflected off the surface of the cornea of the subject being tested and compared in a computer against a reference set of rings stored in the computer as a representation of a non-deformed corneal surface.

It is still an additional object of the present invention to provide a computer driven optical keratometer which may be advantageously used by opthamologists, optometrists and other such eye-related medical personnel for the purpose of evaluating the shape of the corneal surface and wherein a laser light source is used in conjunction with a single reticle pattern to produce a series of rings on the surface of the cornea which is reflected back into an optical focusing assembly and onto an optical sensor which transmits corresponding data to a computer which compares the reflected image with a stored reference image for evaluating the deformation of the cornea.

It is still an additional object of the present invention to provide a novel and advantageous method for nu-

merically evaluating the shape of the cornea using only one reticle-generated ring pattern, the reflection of which is compared on a point-by-point basis with a stored reference pattern.

BRIEF DESCRIPTION OF THE DRAWINGS

The aforementioned advantages and objects of the present invention, as well as additional advantages and objects thereof, will be more fully understood hereinafter as a result of a detailed description of a preferred embodiment when taken in conjunction with the following drawings:

FIG. 1 is a block diagram representation of the optical subsystem of the present invention;

FIG. 1*a* illustrates the pattern of a reticle used in the preferred embodiment of the invention;

FIG. 2 is a schematic diagram of the final focusing lens of the optical system of FIG. 1 shown relative to the eye being measured;

FIG. 3 is a graphical representation illustrating variation in reticle radius and eye viewing radius at various distances from the eye;

FIG. 4 is a schematic diagram illustrating the interrelationship between the eye being measured and rays emanating from the reticle;

FIGS. 4*a* and 4*b* are two enlargements of a portion of FIG. 4 illustrating the mathematical analysis of the deformation measurement process of the present invention;

FIG. 5 is a graphical representation of expected deflection angles and actual deformation for various ring systems and viewing radii;

FIG. 6 is a schematic representation of a portion of the numerical process of the present invention specifically illustrating how the measured angle of deflection of laser generated rings is also dependent upon the focusing distance of the invention;

FIG. 7 is a graphical representation illustrating the relationship between vertical displacement on the focusing lens and total deformation for various ring geometries and focusing distances;

FIG. 8 is an additional schematic diagram illustrating the behavior of certain rays of the apparatus of the present invention; and

FIG. 9 is a graphical representation illustrating the relationship between the deflection angle and eye deformation for various ring systems and lens distances.

DETAILED DESCRIPTION OF THE INVENTION

Referring now first to FIG. 1 it will be seen that the optical subsystem **10** of the present invention comprises a laser **12**, a mirror **14**, a shutter **16**, a microscope objective lens **18**, a pinhole **19**, a collimating lens **20**, a reticle **22**, a beam splitter **24**, a quarterwave plate **26**, focusing assemblies **28** and **30**, a mirror **32** and a video camera **34**, the latter being connected to a computer **36**. Although laser **12** may be any one of numerous lasers it has been found that it is preferable to use a laser operating in the visible light spectrum such as a helium-neon laser. Mirror **14** is be used to bend the light beam emitted by laser **12** so that it enters the microscope objective lens **18** along the proper optical path through a shutter **16**. The shutter is designed to provide the optical subsystem with a pulse of laser light of the appropriate duration for the measurement and may be synchronized, by appropriate electronics (not shown), with the timing of computer **36**. Objective lens **18** and pinhole **19** act in combination to provide a relatively narrow uniform light beam which is then appropriately shaped an redirected by collimating lens **20** to fill reticle **22** with a relatively intense, uniform light source in which all the rings of the reticle **22** (see FIG. 1*a*) receive roughly the same magnitude of incident light energy.

The rings of light produced by reticle **22** are transmitted through a beam splitter **24**, a quarterwave plate **26** and a first focusing assembly **28** which focuses the rings on the eye **5** being measured over a selected circular region having a viewing radius h. The rings of light incident on the eye **5** are reflected by the surface of the cornea. The reflected light passes through focusing assembly **28**, quarterwave plate **26** and enters beam splitter **24** where it is redirected at a **90** degree angle relative to the incident light path into focusing assembly **30**. Focusing assembly **30** is designed to focus the reflected light or ring pattern onto mirror **32** which redirects the reflected light energy into the lens of video camera **34**. Quarterwave plate **26** is designed to direct the light reflected from the eye **5** to the video camera by changing the polarization of the outgoing and incoming light by 90 degrees. The video camera **34** generates a corresponding signal replicating the reflected ring pattern from the eye **5** and transmits it to the computer **36**. Electronics between video camera **34** and computer **36** may be used to configure the video camera electronic signal in an appropriate data output suitable for use by computer **36**. The operation of the video camera **34** as well as the operation of any necessary electronics to configure the corresponding electrical signal to be compatible with a computer are well-known in the art and need not be disclosed herein in any detail.

As previously indicated, computer **36** is provided with a reference pattern, that is, with appropriate data corresponding to a set of reflected rings which would otherwise be received by video camera **34** if the corneal surface of the eye **5** were precisely spherical without any deformation whatsoever anywhere on its surface. It will be recognized that by simply altering the contents of the signal stored in the memory of computer **36**, which signals correspond to the reference pattern to which the reflected pattern is compared by the computer, one can readily alter the reference pattern to any desired configuration. Thus, the optical system **10** of the invention imposes a series of rings generated by passage of light through a reticle onto the eye and captures a series of reflected rings reflected from the surface of the eye. If no deformation exists, then there is no displacement of the rings from a reference set stored in the computer. If there is deformation, it will cause some or all of the rings to be displaced slightly from the reference set and the computer determines the amount of such deformation. The computer numbers and locates the center of each ring and compares it to the corresponding reference ring. The output of computer **36** may be designed to provide different forms of information depending upon the application of the invention. Thus for example, computer **36** may be programmed to simply provide a read out in either diopters or millimeters of the relative radius of curvature of the cornea indicative of a refractive deficiency. On the other hand, computer **36** may be programmed to provide a detailed topographical map which may either be displayed in the form of a set of numerals or as an actual simulated presentation of the cornea shape. The first type of output of computer **36** may be readily used to correct a refractive deficiency of the eye, while the latter is preferable par-

ticularly for surgeons who wish to know precisely what the shape of the eye is before or after corrective surgery. Both types of computer outputs are generated in response to a detailed comparison between the reflected rings and the stored reference rings by computer **36** to determine the extent of corneal deformation. The program used in an embodiment of the invention that has been reduced to practice is designed to produce an output corresponding to the relative radius of curvature of the eye, but could be modified by those having skill in the relevant art to provide a topological map of the eye.

Reference will now be made to FIGS. **2-9** primarily to illustrate the method of the present invention and more specifically, to demonstrate by mathematical analysis at the interface of the rays of light and the real eye surface that the system of the present invention is capable of measuring deformations with necessary accuracy and resolution and to show that the reflected rings are sufficiently displaced by deformation to be analyzed by computer **36**. Table I below defines the nomenclature used in FIGS. **2-9**.

TABLE I

Nomenclature:	
d =	Spacing of rings on the eye, μm
h =	Height above horizontal eye center for viewing (viewing radius), mm
H_1 =	Height above central horizontal ray for Ring N, mm
h_2 =	Height above central horizontal ray for Ring N+1, mm
H =	Reticle radius, mm
l =	Distance from center of eye to point where reflected ray intersects central horizontal ray, mm
L =	Distance from edge of focusing lens to center of eye, mm
r =	Radius of eye, assumed to be approximately .75 inch = 19.05 mm
Points:	
A -	Intersection of N ring and radius of eye
B -	Intersection of N+1 ring and radius of eye
D -	Intersection of Real surface and horizontal line from point B
E -	Intersection of Normal to line AD (from point F) and either line AB or BD
F -	Intersection of Incident of ray of ring N+1 and real surface
G -	Intersection of Reflected ray (from point F) and either line AB or AD
I -	Intersection of Reflected ray projected back and central horizontal ray
M -	Intersection of Reflected ray and focusing lens
O -	Center of eye
P -	Intersection of incident ray from ring N ring and focusing lens
Q -	Intersection of incident ray from ring N+1 ring and focusing lens
S -	Intersection of vertical projection down from point Q and central ray
T -	Intersection of vertical projection down from point M and central ray
Greek:	
α =	Angle between incident ray from ring N and central ray, Degrees
β =	Angle between incident ray from ring N+1 and central ray, Degrees
γ =	$\frac{1}{2}(\alpha+\beta)$, Degrees
δ =	Difference between reference and actual points, measured horizontally, μm
Δ =	Difference between incident and reflected rays, measured vertically, on focusing lens, mm
η =	Angle between N+1 and N rings, Degrees
Θ =	Total viewing angle, Degrees
ξ =	Angle between reflected ray and incident ray at same point on focusing lens, Degrees
Φ =	Angle between reference normal and actual normal, Degrees

FIG. **2** is a schematic diagram of the final focusing lens of focusing assembly **28** and the eye **5** being subjected to evaluation by the invention. FIG. **2** illustrates the lens at a distance L from the center of the eye. In order to view the exterior surface or cornea of the eye up to a height h from the central ray of the eye (represented by the horizontal line in FIG. **2**), the lens radius must be at least height H. FIG. **3** is a graphical representation showing the variation of eye viewing height h with optical radius or reticle radius H for various distances between the final lens and the center of the eye. More specifically, the variation of h with H is shown for distances of 2, 3, 4 and 6 inches respectively. Thus it will be seen that in FIG. **3** that if, for a distance L of 4 inches between the center of the eye and the final lens of the focusing assembly, one desires an eye viewing height h of 8 millimeters, it is necessary to have a reticle or lens height of 50 millimeters. Precise dimensions for the optical section may be varied based on parameters such as cost and preferences of medical personnel.

Referring now to FIGS. **4**, **4***a* and **4***b*, it will be seen that the eye and the rays from the n and n+1 rings are shown schematically therein. The ray from the n ring intersects the actual surface of the eye at A which corresponds with the reference surface. No distortion is assumed at position A. The ray from the n+1 ring intersects the reference surface at B. However, it is assumed for purposes of demonstration that, due to distortion, the actual point of contact between the n+1 ring and the eye surface is at point F. The length of line BD is a measure of the bulging or flatness of the eye at that point.

The triangle ABD is shown in detail in FIG. **4***b*. Line AD is assumed to be the actual surface which ray QB intersects at F. Ray QB is reflected at an angle equal to the angle between QF and the normal to line AD. This angle Φ is crucial because once it is known, the value of line BD or the distortion can be determined. The length of line BD is also dependent upon the length of line AB as well as on the angles α and β which are known from the geometry of the optical system. The length AB is the distance between successive rings.

Examples of deflection angles for various actual deformations for different ring systems and viewing radii are shown in FIG. **5**. As illustrated therein, for reticles in which there are 10, 25 and 50 rings respectively, total deformations up to 100 micrometers per millimeter produce an eye reflection angle or deflection angle Φ less than 6 degrees. Thus, the deflection angles are of the appropriate order of magnitude to be easily measured but are not large enough to escape the optical system. FIG. **5** also shows that the greater the number of rings, the greater is the deflection angle Φ for the same amount of eye deformation.

FIG. **6** demonstrates how the deflection angle Φ corresponds to a vertical displacement on the focusing lens. Displacement is the difference between incident and reflected rays measured vertically on the focusing lens and is also dependent on the focusing distance L. The graph of FIG. **7** shows vertical displacement Δ as it varies with total deformation or the various ring geometries shown in FIG. **5** as well as for different focusing distances L. As seen in FIG. **7**, the larger the focus-

ing distance L, the greater is the displacement for all ring geometries. Also seen in FIG. 7, for two geometries having the same number of rings, the one with the smaller viewing radius produces the greater displacement. It is preferable to choose a focusing distance and a ring geometry which will prevent the displaced rays from escaping the optical limits of the system and which will also avoid the necessity for requiring larger and more expensive optics.

Referring again to FIG. 6 it will be seen that the reflected ray FM, if projected back towards the center of the eye, crosses the central horizontal ray at some distance from the focus. Because ray IM does not originate at the focus, it will not be reflected back from the focusing lens in a horizontal line as would ray AP or ray BQ. Consequently, this will cause the reflected ray to diverge slightly from the horizontal at M. This diverging angle ξ is shown in FIG. 8. This diverging angle can be approximated as equal to the angle made by the ray MF and ray MO where MO is the ray drawn from point M to the focus of the eye. This angle adds additional displacement from the incident ray, but should be kept small to keep all rays within the limits of the optical system.

In this regard, FIG. 9 illustrates this diverging angle ξ as it varies with total deformation for the previously indicated ring system and lens distances. FIG. 9 illustrates that although the longer distances yield higher displacement values, they also produce higher diverging angles. FIGS. 5, 7 and 9 together demonstrate how an actual eye surface, which differs from a reference surface, will give rise to a reflected ray which is displaced from the incident ray on the focusing lens. This displacement is a function of the geometry of the system and its difference from the true surface. In an actual measurement using the present invention, the displacement and deflection angles are measured quantities and the reflection angle and the deformation are generated based upon the following formulas.

$$\Theta = \arcsin(h/r)$$
$$H = L * \tan\Theta$$
$$\eta = \Theta/(\text{Number of Rings})$$
$$\alpha = N * \eta$$
$$\beta = (N+1) * \eta$$
$$h_1 = r * \sin\alpha$$
$$h_2 = r * \sin\beta$$
$$\gamma = Y_2(\alpha+\beta)$$
$$\text{Ring Spacing} = h_2 - h_1$$
$$\delta = \text{Total Deformation} \bullet \text{Ring Spacing}$$
$$AB = [2 \bullet r^2 (1 - \cos\eta)]^{1/2}$$
$$AD = [AB^2 + \delta^2 - 2 \bullet AB \bullet \delta * \cos(90+\gamma)]^{1/2}$$
$$\sphericalangle 6 = \arcsin[(AB/AD)\sin(90^\circ + \gamma)]$$
$$\sphericalangle 5 = 180^\circ - (\sphericalangle 6 + \beta)]$$
$$\Phi = 90^\circ - \sphericalangle 5$$
$$\Delta = MT - QS$$
$$QS = L \bullet \sin\beta$$
$$MT = MI \bullet \sin(2 \bullet \Phi + \beta)$$
$$MI = MF + FI$$
$$FI = (\lambda \bullet \sin\beta)/\sin(2 * \Phi) \text{ where } \lambda = \frac{FO \bullet \sin(2 * \Phi)}{\sin(180^\circ - (2 * \Phi + \beta)}$$
and
$$FO = \frac{r - \delta \sin\sphericalangle 6}{\sin(90^\circ + \Phi)}$$
$$MF = MG + GF$$
$$\text{Since } GF << MG, \text{ then } MF = MG$$
$$MG = L - r$$
$$\xi = 2 \bullet \Phi + \beta - \arcsin(MT/L)$$

The computer software for carrying out the numerical analysis in accordance with the equations above for measured deflection angles and displacement is provided herein in Table II.

TABLE II

List of POLYCOR2.BAS

```
10    REM POLYNOMIAL REGRESSION FOR THE CORNEA TASK
20    DIM C(50), B(50)
30    FOR I=1 TO 5
40    C(I)=0
50    B(I)=0
60    NEXT I
70    FOR I=6 TO 36
80    C(I)=0
90    NEXT I
100   B(1)=1
110   W=0:N=0:S1=0:S2=0:S3=0:S4=0:S5=0
120   PRINT "MAX.  DEGREE= ";
130   INPUT D2:LPRINT
140   LPRINT "MAX DEGREE = ";D2
150   LPRINT
160   PRINT "MAX NO. POINTS";
170   INPUT Q
180   LPRINT
190   PRINT "ENTER DATA";
200   LPRINT "DATA USED":LPRINT
210   IF W=0 THEN 230
220   PRINT "NOT ALLOWED";
```

```
230   IF N<>0 THEN 270
240   LPRINT "NO.";
250   LPRINT TAB(16);"X"
260   LPRINT TAB(30) ;"Y"
270   PRINT "X=? , Y=";
290   INPUT B(2) , Y
300   LPRINT N+1 , B(2) , Y
310   Z=1
320   FOR I=2 TO D2
330   B(I+1)=B(I)*B(2)
340   NEXT I
350   B(D2+2)=Y
360   R=0
370   FOR I=1 TO D2+2
380   FOR J=I TO D2+2
390   R=R+1
400   C(R)=C(R)+B(I)*B(J)*Z
410   NEXT J
420   NEXT I
430   S1=S1 + B(2)*Z
440   S2=S2+B(2)^2*Z
450   S3=S3 + Y*Z
460   S4=S4 + Y*Y*Z
470   S5=S5+B(2)*Y*Z
480   N=N+Z
490   IF N=Q THEN 510
500   GOTO 270
510   IF N<=D2-W THEN 890
520   PRINT "HOW MANY COEF.; MUST LESS THAN MAX NO. OF DEG. =";
530   INPUT D1
540   LPRINT
550   LPRINT "NO.COEF. REQ. =";D1
560   IF D1<D2-W THEN 580
570   PRINT "MAX DEG =";D2-W
580   IF W=0 THEN 880
590   T=0
600   FOR I=1 TO D1+1
610   B(I)=0
620   FOR J=1 TO D1-I+2
630   R=(I+J-1)*(D2+2-.5*(I+J))
640   B(I)=B(I)+C(T+J)*C(R)
650   NEXT J
660   T=I*(D2+(3-I)/2)
670   NEXT I
680   R1=0
690   FOR I=2 TO D1+1
700   R1=R1+C(I*(D2+(3-I)/2))^2
710   NEXT I
720   T0=C((D2+1)*(D2+2)/2)
730   T0=T0-C(D2+1)^2
740   LPRINT
750   LPRINT "COEFFICIENTS"
760   LPRINT
770   REM
780   FOR I=1 TO D1+1
790   LPRINT "B(";I-1;") =";
800   LPRINT USING "##.###^^^^";B(I)
810   NEXT I
820   LPRINT
```

```
830   LPRINT
840   LPRINT "R SQUARE =";
850   LPRINT USING "##.###^^^^";R1/TO
860   LPRINT
870   GOTO 1330
880   IF N>D2 THEN 900
890   PRINT "NOT ENOUGH POINTS";
900   P=1
910   W=1
920   D2=D2+1
930   FOR J=1 TO D2
940   IF C(P)>=0 THEN 970
950   LPRINT "MATRIX UNSTABLE - USE LOWER MAX. DEGREE !"
960   LPRINT
970   C(P)=SQR(C(P))
980   FOR I=1 TO D2-J+1
990   C(P+I)=C(P+I)/C(P)
1000  NEXT I
1010  R=P+I
1020  S=R
1030  FOR L=1 TO D2-J
1040  P=P+1
1050  FOR M=1 TO D2+2-J-L
1060  C(R+M-1)=C(R+M-1)-C(P)*C(P+M-1)
1070  NEXT M
1080  R=R+M-1
1090  NEXT L
1100  P=S
1110  NEXT J
1120  T=(D2+1)*(D2+2)/2
1140  FOR I=1 TO D2-1
1150  T=T-1-I
1160  C(T)=1/C(T)
1170  FOR J=1 TO D2-I
1180  P=D2+1-I-J
1190  P=P*(D2+1-(P-1)/2)-I
1200  R=P-J
1210  S=0
1220  U=I+J+1
1230  V=P
1240  FOR K=1 TO J
1250  V=V+U-K
1260  S=S-C(R+K)*C(V)
1270  NEXT K
1280  C(P)=S/C(R)
1290  NEXT J
1300  NEXT I
1310  C(1)=1/C(1)
1320  GOTO 570
1330  LPRINT
1340  LPRINT "                    STATISTICS"
1350  LPRINT
1360  S8=SQR((S2-S1^2/N)/(N-1))
1370  S9=SQR((S4-S3^2/N)/(N-1))
1380  R9=(S5-S1*S3/N)/(N-1)/S8/S9
1390  LPRINT
1400  LPRINT "NO. POINTS = ";N
1410  LPRINT
1420  LPRINT "X: MEAN = ";
```

```
1430 LPRINT USING "##.###^^^^";S1/N;
1440 LPRINT TAB(25);"STD DEV =";
1450 LPRINT USING"##.###^^^^";S8
1460 LPRINT"Y: MEAN =";
1470 LPRINT USING "##.###^^^^";S3/N
1480 LPRINT TAB(25);"STD DEV =";
1490 LPRINT USING "##.###^^^^";S9
1500 LPRINT
1510 LPRINT "CORR COEFF =";
1520 LPRINT USING "##.###^^^^";R9
1530 LPRINT
1540 PRINT "DO YOU WANT TO DO ESTIMATE, TABLE, OR STOP.
1550 INPUT G$
1560 IF G$="E" THEN 1590
1570 IF G$="T" THEN 1650
1580 IF G$="S" THEN 1810
1590 LPRINT "                    ESTIMATE"
1600 PRINT "X=";
1610 INPUT A
1620 B(I)=A
1630 C(I)=1
1640 GOTO 1690
1650 LPRINT "                TABLE"
1660 PRINT
1670 PRINT "XMIN,XMAX,STEP=";
1680 INPUT A,B(I),C(I)
1690 LPRINT
1700 FOR I=A TO B(I) STEP C(I)
1710 Y=B(D1+1)
1720 FOR J=D1 TO 1 STEP -1
1730 Y=Y*I+B(J)
1740 NEXT J
1750 LPRINT "X=";
1760 LPRINT USING "##.###^^^^";I;
1770 LPRINT TAB(20);"Y=";
1780 LPRINT USING "##.###^^^^";Y
1790 NEXT I
1800 GOTO 1540
1810 STOP
1820 END
```

List of CURSOR59.BAS

```
10    REM FIRST CONT.DIGITIZE THEN FREEZE
20    REM
30    REM MOVE CURSOR ROUTINE
40    REM
50    OUT 164,INIT
60    FOR I=1 TO 2
70    WAIT &HA4,2,2
80    OUT &HA2,&H10
90    OUT &HA3,&H00
100   WAIT &HA4,2,2
110   OUT &HA2,&H0B
120   OUT &HA3,&H00
130   WAIT 164,2,2
140   OUT &HA2,&H38
150   OUT &HA3,&H00
```

```
160   WAIT &HA4,2,2
170   OUT &HA0,&H01
180   OUT &HA1,&H00
190   WAIT &HA4,2,2
200   OUT &HA2,&H3D
210   OUT &HA3,&H00
220   WAIT &HA4,2,2
230   OUT &HA0,&H01
240   OUT &HA1,&H00
250   WAIT &HA4,2,2
260   OUT &HA2,&H39
270   OUT &HA3,&H00
280   NEXT I
290   REM
300   REM CURSOR DISPLAY
310   REM
320   WAIT &HA4,2,2
330   OUT &HA2,26
340   OUT &HA3,0
350   WAIT &HA4,2,2
360   OUT &HA2,27
370   OUT &HA3,0
380   WAIT &HA4,2,2
390   OUT &HA0,1
400   OUT &HA1,0
410   T=0
420   INPUT "",MOV$
430   if mov$="1" then 440 else 490
440   M=0
450   X=0
460   Y=1
470   N=0
480   GOTO 1380
490   if mov$="11" then 500 else 550
500   m=0
510   x=0
520   y=10
530   n=0
540   goto 1380
550   if mov$="2" then 560 else 610
560   M=0
570   X=0
580   Y=&HFF
590   N=&HFF
600   goto 1380
610   if mov$="22" then 620 else 670
620   m=0
630   x=0
640   y=&Hf6
650   n=&HFF
660   goto 1380
670   if mov$="3" then 680 else 730
680   M=0
690   X=1
700   Y=0
710   N=0
720   GOTO 1380
730   if mov$="33" then 740 else 790
740   m=0
```

```
750   x=10
760   y=0
770   n=0
780   goto 1380
790   if mov$="4" then 800 else 850
800   M=&HFF
810   X=&HFF
820   Y=0
830   N=0
840   GOTO 1380
850   if moV$="44" then 860 else 910
860   m=&HFF
870   x=&HF6
880   y=0
890   n=0
900   goto 1380
910   if mov$="5" then 920 else 970
920   M=0
930   X=1
940   Y=1
950   N=0
960   GOTO 1380
970   if mov$="55" then 980 else 1030
980   m=0
990   x=10
1000  y=10
1010  n=0
1020  goto 1380
1030  if mov$="6" then 1040 else 1090
1040  M=&HFF
1050  X=&HFF
1060  Y=&HFF
1070  N=&HFF
1080  GOTO 1380
1090  if mov$="66" then 1100 else 1150
1100  M=&HFF
1110  x=&HF6
1120  y=&hF6
1130  N=&HFF
1140  goto 1380
1150  if mov$="7" then 1160 else 1210
1160  M=&HFF
1170  X=&HFF
1180  Y=1
1190  N=0
1200  GOTO 1380
1210  if mov$="77" then 1220 else 1270
1220  M=&HFF
1230  x=&hF6
1240  y=10
1250  n=0
1260  goto 1380
1270  if mov$="8" then 1280 else 1330
1280  M=0
1290  X=1
1300  Y=&HFF
1310  N=&HFF
1320  goto 1380
1330  if mov$="88" then 1340 else 1470
```

```
1340  M=0
1350  x=10
1360  y=&Hf6
1370  n=&HFF
1380  WAIT &HA4,2,2
1390  OUT &HA2,25
1400  OUT &HA3,0
1410  WAIT &HA4,2,2
1420  OUT &HA0,X
1430  OUT &HA1,M
1440  WAIT &HA4,2,2
1450  OUT &HA0,Y
1460  OUT &HA1,N
1470  IF MOV$="N" THEN 1480 ELSE 1640
1480  wait &Ha4,2,2
1490  OUT &HA2,124
1500  OUT &HA3,0
1510  WAIT &HA4,1,0
1520  DX=INP(160)
1530  DX1=INP(161)
1540  IF DX1=255 THEN 1550 ELSE 1570
1550  DX1=DX1-256
1560  DX=DX-256
1570  WAIT &HA4,1,0
1580  DY=INP(160)
1590  DY1=INP(161)
1600  IF DY1=255 THEN 1610 ELSE 1630
1610  DY1=DY1-256
1620  DY=DY-256
1630  PRINT TAB(20);DX,TAB(40);DY
1640  IF MOV$="F" THEN 1650 ELSE 420
1650  rem
1660  rem set cursor location as new coordinate origin
1670  rem
1680  wait &Ha4,2,2
1690  out &HA2,23
1700  out &HA3,0
1710  wait &HA4,2,2
1720  OUT &HA0,DX
1730  OUT &HA1,DX1
1740  WAIT &HA4,2,2
1750  OUT &HA0,DY
1760  OUT &HA1,DY1
1770  wait &HA4,2,2
1780  OUT &HA2,124
1790  out &Ha3,0
1800  wait &Ha4,1,0
1810  XORIGN=INP(&HA0)
1820  XORIGN1=INP(&HA1)
1830  WAIT &HA4,1,0
1840  YORIGN=INP(&HA0)
1850  YORIGN1=INP(&HA1)
1860  PRINT TAB(20);XORIGN;TAB(30);YORIGN
1870  OPEN "R", #1, "TOPODATA", 100
1880  INPUT "",MOV$
1890  if mov$="1" then 1900 else 1950
1900  M=0
1910  X=0
1920  Y=1
```

```
1930 N=0
1940 GOTO 2860
1950 if mov$="11" then 1960 else 2010
1960 m=0
1970 x=0
1980 y=10
1990 n=0
2000 goto 2860
2010 if mov$="2" then 2020 else 2070
2020 M=0
2030 X=0
2040 Y=&HFF
2050 N=&HFF
2060 goto 2860
2070 if mov$="22" then 2080 else 2130
2080 m=0
2090 x=0
2100 y=&Hf6
2110 n=&HFF
2120 goto 2860
2130 if mov$="3" then 2140 else 2190
2140 M=0
2150 X=1
2160 Y=0
2170 N=0
2180 GOTO 2860
2190 if mov$="33" then 2200 else 2250
2200 m=0
2210 x=10
2220 y=0
2230 n=0
2240 goto 2860
2250 if mov$="4" then 2260 else 2310
2260 M=&HFF
2270 X=&HFF
2280 Y=0
2290 N=0
2300 GOTO 2860
2310 if moV$="44" then 2320 else 2370
2320 m=&HFF
2330 x=&HF6
2340 y=0
2350 n=0
2360 goto 2860
2370 if mov$="5" then 2380 else 2430
2380 M=0
2390 X=1
2400 Y=1
2410 N=0
2420 GOTO 2860
2430 if mov$="55" then 2440 else 2490
2440 m=0
2450 x=10
2460 y=10
2470 n=0
2480 goto 2860
2490 if mov$="6" then 2500 else 2550
2500 M=&HFF
2510 X=&HFF
```

```
2520 Y=&HFF
2530 N=&HFF
2540 GOTO 2860
2550 if mov$="66" then 2560 else 2630
2560 M=&HFF
2570 x=&HF6
2580 PRINT TAB(50);X
2590 y=&hF6
2600 PRINT TAB(55);Y
2610 N=&HFF
2620 goto 2860
2630 if mov$="7" then 2640 else 2690
2640 M=&HFF
2650 X=&HFF
2660 Y=1
2670 N=0
2680 GOTO 2860
2690 if mov$="77" then 2700 else 2750
2700 M=&HFF
2710 x=&hF6
2720 y=10
2730 n=0
2740 goto 2860
2750 if mov$="8" then 2760 else 2810
2760 M=0
2770 X=1
2780 Y=&HFF
2790 N=&HFF
2800 goto 2860
2810 if mov$="88" then 2820 else 2970
2820 M=0
2830 x=10
2840 y=&Hf6
2850 n=&HFF
2860 WAIT &HA4,2,2
2870 OUT &HA2,25
2880 OUT &HA3,0
2890 WAIT &HA4,2,2
2900 OUT &HA0,X
2910 PRINT X
2920 OUT &HA1,M
2930 WAIT &HA4,2,2
2940 OUT &HA0,Y
2950 PRINT Y
2960 OUT &HA1,N
2970 IF MOV$="R" THEN 3140 ELSE 2980
2980 wait &Ha4,2,2
2990 OUT &HA2,124
3000 OUT &HA3,0
3010 WAIT &HA4,1,0
3020 DX=INP(160)
3030 DX1=INP(161)
3040 IF DX1=255 THEN 3050 ELSE 3070
3050 DX1=DX1-256
3060 DX=DX-256
3070 WAIT &HA4,1,0
3080 DY=INP(160)
3090 DY1=INP(161)
3100 IF DY1=255 THEN 3110 ELSE 3130
```

```
3110  DY1=DY1-256
3120  DY=DY-256
3130  PRINT
3140  INPUT "DO YOU WANT CURSOR POSITION RECORDED (Y/N)";Q$
3150  IF Q$="Y" THEN 3170 ELSE 1880
3160  RO=SQR(RXO^2+RYO^2)
3170  GOSUB 3660
3180  INPUT "NEXT DATA POINT PAIR OR (E) TO EXIT";R$
3190  IF R$="E" THEN 3210 ELSE 3200
3200  GOTO 1880
3210  GOSUB 3750
3220  FOR T=1 TO T
3230  GET #1,T
3240  R1XO=CVI(R1XO$)
3250  RXO=CVI(RXO$)
3260  R1YO=CVI(R1YO$)
3270  RYO=CVI(RYO$)
3280  RO=SQR(RXO^2+RYO^2)
3290  CALF=0.4666
3300  ROMM=RO*CALF
3310  PRINT TAB(30);ROMM
3320  NEXT T
3330  WAIT &HA4,2,2
3340  OUT &HA2,124
3350  OUT &HA3,0
3360  WAIT &HA4,1,0
3370  DX=INP(160)
3380  DX1=INP(161)
3390  WAIT &HA4,1,0
3400  DY=INP(160)
3410  DY1=INP(161)
3420  WAIT &HA4,2,2
3430  OUT &HA2,25
3440  OUT &HA3,0
3450  WAIT &HA4,2,2
3460  PRINT
3470  PRINT "DX IS = ";DX
3480  PRINT "DX1 IS = ";DX1
3490  PRINT "DY IS = ";DY
3500  PRINT "DY1 IS = ";DY1
3510  DX=256-DX
3520  DX1=255
3530  OUT &HA0,DX
3540  OUT &HA1,DX1
3550  WAIT &HA4,2,2
3560  DY=256-DY
3570  DY1=255
3580  PRINT DX
3590  PRINT DX1
3600  PRINT DY
3610  PRINT DY1
3620  OUT &HA0,DY
3630  OUT &HA1,DY1
3640  GOTO 1880
3650  CLOSE:END
3660  FIELD #1, 20 AS R1XO$, 20 AS RXO$, 20 AS R1YO$, 20 AS RYO$
3670  T=T+1
3680  PRINT "T IS NOW =  ";T
3690  LSET R1XO$=MKI$(DX1)
```

```
3700 LSET RXO$=MKI$(DX)
3710 LSET R1YO$=MKI$(DY1)
3720 LSET RYO$=MKI$(DY)
3730 PUT #1,T
3740 RETURN
3750 PRINT TAB(30);"FRINGE RADII"
3760 PRINT
3770 IF MOV$="3" THEN 3790 ELSE 3780
3780 IF MOV$="33" THEN 3790 ELSE 3820
3790 PRINT TAB(31);"AZIMUTH 0"
3800 PRINT
3810 GOTO 3220
3820 IF MOV$="4" THEN 3840 ELSE 3860
3830 IF MOV$="44" THEN 3840 ELSE 3860
3840 PRINT TAB(20);"AZIMUTH 180"
3850 PRINT
3860 IF MOV$="1" THEN 3880 ELSE 3910
3870 IF MOV$="11" THEN 3880 ELSE 3910
3880 PRINT TAB(31);"AZIMUTH 90"
3890 PRINT
3900 GOTO 3220
3910 IF MOV$="2" THEN 3930 ELSE 3920
3920 IF MOV$="22" THEN 3930 ELSE 3960
3930 PRINT TAB(31);"AZIMUTH 270"
3940 PRINT
3950 GOTO 3220
3960 IF MOV$="5" THEN 3980 ELSE 3970
3970 IF MOV$="55" THEN 3980 ELSE 4010
3980 PRINT TAB(31);"AZIMUTH 45"
3990 PRINT
4000 GOTO 3220
4010 IF MOV$="6" THEN 4030 ELSE 4020
4020 IF MOV$="66" THEN 4030 ELSE 4060
4030 PRINT TAB(31);"AZIMUTH 225"
4040 PRINT
4050 GOTO 3220
4060 IF MOV$="7" THEN 4080 ELSE 4070
4070 IF MOV$="77" THEN 4080 ELSE 4110
4080 PRINT TAB(31);"AZIMUTH 135"
4090 PRINT
4100 GOTO 3220
4110 IF MOV$="8" THEN 4130 ELSE 4120
4120 IF MOV$="88" THEN 4130 ELSE 4150
4130 PRINT TAB(31);"AZIMUTH 315"
4140 PRINT
4150 RETURN
```

It will now be understood that what has been disclosed herein comprises a laser beam keratometer having only one optical reticle. The keratometer provides an optical subsystem designed to impose a series of rings generated by a reticle on the surface of the eye and to capture a series of reflected rings from the eye. The image of reflected rings is transmitted to a computer which effectively superimposes a computer stored reference image on the image reflected from a subject's eye. Data processing numerical analysis then provides a real time display or numerical information on the condition of the eye. When no deformation exists there is no displacement of the rings from the reference set stored in the computer. However, any deformation that is observed causes some or all of the rings to be displaced slightly from the reference set and the computer analyzes the amount of deformation to produce either a detailed topology of the eye or a simpler numerical representation of the eye's refractive condition. The real time or near real time capabilities of the present invention are particularly advantageous for use in medical diagnosis and evaluation of the corneal contour for eye surgery as well as for evaluation of the corneal contour post-operatively. The present system provides corneal contour evaluation over a much larger surface area than previously possible using prior art keratome-

ters. Furthermore, the novel use of one reticle-produced image, the eye's reflection of which is compared against a reference image in a computer, alleviates prior art alignment problems and resulting fringes.

Those having skill in the art to which the present invention pertains will now, as a result of the disclosure herein, perceive various modifications and additions which may be made to the invention. Thus for example, while FIG. 1 demonstrates an illustrative embodiment of an apparatus configured to accomplish the method of the invention, it will be understood that other optical subsystems may be utilized to generate the reflected image used by the computer in calculating the deformation and surface characteristics of the cornea. Furthermore, while it will be observed that a particular reticle geometry has been used herein, other reticle geometries and corresponding modified numerical analyses may be readily employed to accomplish essentially the same method as disclosed herein or a method substantially equivalent thereto. Consequently, it will be understood that all such modifications and additions are contemplated as being within the scope of the invention which is to be limited only by the claims appended hereto.

We claim:

1. An apparatus for measuring the shape of a cornea, the apparatus of the type having a source of light and an optical assembly for focusing said light onto the cornea and for directing reflected light from the cornea onto an imaging device; the apparatus comprising:

a single reticule for interrupting a portion of said light to form a selected pattern on the cornea, said pattern being deformable by an irregularly shaped cornea as said pattern is reflected by the cornea and appears on said imaging device; and,

means for measuring the deformation of said reflected patern and for determining the shape of the cornea therefrom, said measuring and determining means comprising a digital computer programmed to compare said reflected pattern with a reference pattern stored in said computer, said programmed digital computer automatically aligning said reflected pattern with said reference pattern prior to calculating differences therebetween for quantitatively characterizing said shape of said cornea.

2. The apparatus recited in claim 1 wherein said reticle pattern comprises a series of concentric rings.

3. The apparatus recited in claim 2 wherein the number of rings in said reticle pattern is in the range of 10 to 50.

4. The apparatus recited in claim 2 wherein the radius of said reticle pattern is less than four inches.

5. The apparatus recited in claim 1 wherein said source of light is a laser.

6. The apparatus recited in claim 5 wherein said laser is a Helium-Neon laser.

7. The apparatus recited in claim 1 wherein said imaging device is a video camera.

8. The apparatus recited in claim 7 wherein said video camera is of the type having a solid state imaging sensor.

9. The apparatus recited in claim 8 wherein said sensor is a charge coupled device.

10. The apparatus recited in claim 1 wherein said reference pattern corresponds to a regularly shaped cornea.

11. The apparatus recited in claim 1 wherein said computer is programmed to measure the vertical distance at the focusing assembly and the angle between the incident and reflected points of said pattern and derive therefrom the angle between the irregular surface normal and the regular surface normal and the horizontal distance between the actual and reference points at the cornea.

12. A method of measuring the shape of the cornea of a subject's eye, the method comprising the steps of:

(a) focusing a selected pattern of light on he cornea for reflection of said pattern therefrom;

(b) focusing the reflected pattern on an imaging sensor for generating an electrical signal representation of said reflected pattern;

(c) transferring said representation of said reflected pattern to a computer having stored therein a pattern representation of a non-deformed cornea;

(d) automatically aligning said representation of said reflected pattern with said stored pattern representation of a non-deformed cornea by determining a center point for said reflected pattern and effectively superimposing a corresponding center point of said stored pattern representation of a non-deformed cornea for calculating any differences between said reflected pattern representation and said non-deformed cornea pattern representation relative to said superimposed center points; and,

(e) calculating the deformation of subject's cornea based upon said calculated differences between said reflected pattern representation and said non-deformed cornea pattern representation.

13. The method recited in claim 12 wherein in step (a) said selected pattern is generated by transmitting light, emitted by a source, through a reticle.

14. The method recited in claim 12 further comprising the step of displaying an image representing the shape of the subject's cornea.

15. The method recited in claim 12 wherein said measuring step comprises the steps of measuring the vertical distance between corresponding points on said pattern representations at a focusing plane spaced from the cornea and measuring the angle between rays passing through said corresponding points.

16. The method recited in claim 15 wherein said calculating step comprises the steps of solving equations based upon said measuring steps to calculate the angle between the corresponding normals to the subject's cornea surface and the non-deformed cornea surface and to calculate the horizontal distance between corresponding points on the subject's cornea surface and the non-deformed cornea surface.

* * * * *